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Performance improvement of PMSM using a Cascade MPC control structure

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ABSTRACT

This paper is based on a cascade model predictive control scheme with an embedded disturbance model. This is done by using the cascade MPC structure for a PMSM with current and speed control as the inner and outer loops are done respectively. The inner loop control is done by Receding horizon using the linearized per unit model of PMSM. The outer loop is also MPC with speed reference as the set point signal, and current as control signal. And the disturbance model is generated and it is included in the denominator of the transfer function of the motor to reduce the periodic disturbance raised from the current sensor, which is the main reason for the formation of the oscillation in the speed of the motor and degradation of the performance of the drive.

Index Terms – embedded disturbance model, model predictive control (MPC).

1. INTRODUCTION

Permanent-magnet synchronous motors (PMSMs) have been broadly adopted for industrial speed control applications due to their low volume and high efficiency. One of the most conventional structure known as field-oriented control, where control schemes for a PMSM is a cascade both the inner-and outer-loop controllers are proportional plus integral. The inner-loop controller regulates the currents in the d –q rotating reference frame, and its outer-loop counterpart regulates the speed by providing the q -axis reference current for the inner loop. This structure is most often applied to maintain constant speed, but performance is degraded as a result of the pulsating torque existing in the motor drive. Pulsating torque in a PMSM is usually produced by various sources, including cogging torque, flux harmonics, and current sensor errors and consists of the 1st, 2nd, 6th, and 12th harmonics, and the fundamental is the synchronous frequency. The high-frequency ripples could be removed by the load inertia or the bandwidth of speed control loop, but the low-frequency ripples that occur within the bandwidth could still cause oscillations in the speed. Among these, the first harmonic is often the major cause of poor control performance due to the sensor offset error, and if suitable compensation is not applied, the speed will oscillate in the steady state, particularly at low values.

A number of controller design methods have been proposed to suppress the torque disturbance and/or the resulting speed ripples, and they can be categorized under feed forward compensation and internal model principle (IMP) approaches, respectively. For example, a feed forward approach is employed to calculate the torque ripples from the feedback errors and feeds forward the correction to cancel the disturbance on the q -axis current. A sizable body of literature addresses the rejection of periodic disturbance based on IMP, which states that, in order to follow a periodic reference or reject a periodic disturbance, the corresponding generating polynomials must be included as part of the denominator polynomial of the controller.

Another possible candidate for electrical drives is model predictive control (MPC), which is an optimization-based approach where the current control applied is obtained by minimizing the difference between the predicted behavior of system and its desired performance. This form of control action is long established in process control where often use of a relatively large sample time is possible, and hence, it is possible to solve the quadratic programming (QP) problem that arises in the resulting algorithm online. Conversely, MPC is less commonly encountered in electric drives and power electronics due to the fast sampling requirement and the computational load of the QP. In more recent years, with the development of faster microcontrollers and advances in MPC research, there has been increasing interest in developing new control schemes based on MPC for the application to electric drives.

One well-researched approach under the general MPC heading is predictive current control (PCC) that takes the advantage of the inherent features of an inverter where, for each of its legs, there are only a finite number of possible switching states available for turning off or on its gates. The underlying idea of PCC is that a one- or two-step-ahead prediction of the stator current is carried out for each of the possible switching states and the one that minimizes the cost function used is selected as the machine input. Depending on the application, the cost function may be formulated to include, for example, the error between the prediction and the reference vector, or the number of switches per cycle and power losses.

Since there are only a finite number of choices for the input, PCC is also termed finite control set MPC in some of the literature. Several different PCC schemes have been proposed, and for example, Morel et al analyze and compare their performance. In general terms, the main features of a PCC-based scheme are relatively fast dynamic response, the ability to impose constraints, and the possible absence of a modulator.

In application to power converters and electric drives, PCC differs from the conventional MPC through the use of a longer prediction horizon and the computation of the optimal inputs under constraints for a linear multivariable system. The application of conventional MPC to an induction motor has been reported, and, the application of conventional MPC to a PMSM has been reported. In, a combination of speed and current control in a single controller is applied to a full-order electromechanical model of a PMSM in the d – q reference frame. Constraints are also imposed, and the resulting input voltage vector must be implemented by the modulator. To deal with the problem of unmeasured disturbance, an extra integrator is superimposed on the MPC to remove the steady-state error.

An MPC design is given for the current loop with the estimation of disturbances using recursive least squares that were fed forward for compensation. This design requires knowledge of the steady-state values because an integrator is not included in the design. More recently, predictive functional control, a type of MPC where the input is modeled by basic functions, has been considered for speed control of a PMSM, where the cascade structure is combined with an extended state observer to compensate for the effects of disturbances. The disturbance rejection analysis in is based on using a disturbance observer.

In this paper we are going to control the speed and current of the motor. So in order to detect the actual speed and the actual current, the rotor position sensor and the current sensor like Hall Effect sensors are used respectively. If the current sensor produces the current sensor offset error, a periodic disturbance will arise. The current sensor offset means if the signal at the input is not sensed and transferred correctly to the output, an error occurs. This periodic disturbance is the main reason for the formation of the

oscillation in the speed of the motor and this degrades the performance of the drive. So a cascade MPC structure for a PMSM with current and speed control as the inner and outer loops are done respectively for performance improvement.

2. RESEARCH BACKGROUND

A. PMSM

Permanent magnet Synchronous motors are widely used in industrial servo-applications due to its high-performance characteristics. PMSMs have the rotor winding replaced by permanent magnets. PMSMs generally have the same operating principle as synchronous machines in general operation at synchronous speed. These motors have several advantages over synchronous motors with rotor field windings. They are elimination of copper loss, higher power density and efficiency, lower rotor inertia, larger air gaps possible because of larger coercive force densities.

B. Model predictive control

Model Predictive Control (MPC) is a multivariable control algorithm that uses:

- an internal dynamic model of the process
- a history of past control moves and
- An optimization cost function J over the receding prediction horizon, to calculate the optimum control moves.

The optimization cost function is given by

$$J = \sum_{i=1}^{N} Wxi(ri - xi)2_{+} \sum_{i=1}^{N} w\Delta u\, i^2$$

Without violating constraints

With x_i = i -th controlled variable

r_i = i -th reference variable

u_i = i -th manipulated variable (e.g. control valve)

w_{xi} = weighting coefficient reflecting the relative importance of x_i

w_{ui} = weighting coefficient penalizing relative big changes in u_i etc.

3. BLOCK DIAGRAM

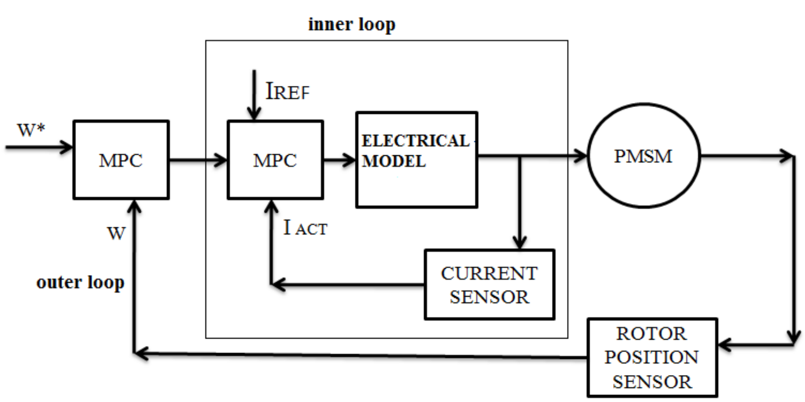

Figure 1 Block Diagram of PMSM Control Using Cascade MPC

The proposed block diagram consists of following modules.

1. PMSM Model.
2. Embedding Signal Generator.
3. Inner Loop MPC.
4. Outer Loop MPC.

PMSM Model

The commonly used d –q model of a PMSM is given in terms of its rotor reference frame as

$$\frac{di_d}{dt} = \frac{1}{L_d}\left(V_d - R_s i_d + w_e L_q i_q\right) \quad (1)$$
$$\frac{di_q}{dt} = \frac{1}{L_d}\left(V_q - R_s i_q - w_e L_d i_d - w_e \emptyset_{mg}\right) \quad (2)$$
$$\frac{dw_e}{dt} = \frac{p}{J}\left(T_e - \frac{B_v}{p} w_e - T_L\right) \quad (3)$$
$$T_e = \frac{3}{2} p[\emptyset_{mg} i_q + (L_d - L_q) i_d i_q] \quad (4)$$

where ω_e is the electrical speed and is related to the rotor speed by $\omega_e = p\omega_m$, with p denoting the number of pole pairs, ω_m denoting the mechanical speed, v_d and v_q denoting the stator voltages in the d –q frame, i_d and i_q denoting the stator currents in the d –q frame, and TL denoting the load torque. The description of the physical parameters for the motor used in this paper is given in Table I.

Table 1 Parameters of PMSM

Sym	Description	SI Value	SI Unit	Per Unit
J	Total inertia	0.47e-4	$Kg.m^2$	0.0267
B_v	Viscous coeff.	1.1e-4	N.m.s	0.0625
L_d	d-axis inductance	7.0e-3	H	0.4120
L_q	q-axis inductance	7.0e-3	H	0.4120
T_L	Load torque	0	Nm	0
R_s	Resistance	2.98	Ohm	0.2781
φ_{mg}	Flux linkage due to permenant magnet	0.125	Wb	0.9102
i_{rated}	Nominal current	2.9	A	0.36
p	No. of poles	2		

Embedding Signal Generator

To follow a reference signal and reject a disturbance with zero steady-state error, the generating polynomial of the reference and disturbance has to be included in the denominator of the controller transfer function. When the reference signal for an application contains multiple frequencies. Then, the resulting generating polynomial will contain all periodic modes and the number of these is proportional to the period of reference/disturbance signal and inversely proportional to the sampling interval. In the case of the reference signal, once the significant frequency components have been selected, the generating polynomial is available, and the design proceeds by first augmenting the plant state-space model with the modes selected from the frequency response of the reference signal. By the IMP, to follow a reference signal and reject a disturbance with zero steady-state error, the generating polynomial of the reference and disturbance has to be included in the denominator of the controller transfer function. This is also termed embedding the signal generator. Consider the case when the reference signal for an application contains multiple frequencies. Then, the resulting generating polynomial will contain all periodic modes and the number of these is proportional to the period of reference/disturbance signal and inversely proportional to the sampling interval. The result could be a very high order control system, particularly under fast sampling, and, hence, the possibility of numerical sensitivity, noise amplification, sensitivity to modeling errors, and other undesirable problems in practical applications.

An alternative to including all the periodic modes is to embed fewer periodic modes at a given instance. In particular, the frequency components of a given signal are analyzed, and its reconstruction is performed using a frequency sampling filter model, from which the significant frequencies are identified and error analysis is used to justify the selections. In the case of the reference signal, once the significant frequency components have been selected, the generating polynomial is available, and the design proceeds by first augmenting the plant state-space model with the modes selected from the frequency response of the reference

signal. Receding horizon control is then applied to this augmented model, and the extension to also include disturbance rejection is immediate. In, the generating polynomial of a general periodic signal is derived from a frequency sampling filter decomposition. Application to the PMSM requires tracking of a constant reference speed and rejection of the sinusoidal and constant load torque disturbances.

Inner Loop MPC

The inner-loop MPC uses the electrical model which is a nonlinear and coupled multivariable system with control signals v_d and v_q and the output signals id and i_q. The first step is to linearize this model about the steady-state operating condition defined by the parameters ω_{e0}, i_{d0}, and i_{q0}, resulting in the following linearized model for the d –q -axis current:

$$\begin{bmatrix} \frac{di_d}{dt} \\ \frac{di_q}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{R_s}{L_d} & \frac{L_q}{L_d} w_{e0} \\ -\frac{L_d}{L_q} w_{e0} & -\frac{R_s}{L_q} \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} \frac{1}{L_d} & 0 \\ 0 & \frac{1}{L_q} \end{bmatrix} \begin{bmatrix} v_d \\ v_q \end{bmatrix} + \begin{bmatrix} \frac{L_q}{L_d} i_{q0} w_e \\ -\frac{\emptyset_{mg}}{L_q} w_e - \frac{L_d}{L_q} i_{d0} w_e \end{bmatrix} \qquad (5)$$

The primary roles of inner-loop control system are to reject the disturbances as fast as possible and to overcome the non-linearity and parameter uncertainties. The relative simplicity of implementation of the real-time control system partially justifies embedding integrators into the design of MPC for the inner loop where all variables are expressed in incremental form, and hence, information concerning the steady-state operation, such as the parameters i_{d0}, i_{q0}, v_{d0}, and v_{q0}, is not required for this task.

Outer Loop MPC

With input i_q, output ω_e, and

$$\frac{dw_e}{dt} = \frac{p}{J}\left(\frac{3}{2} p i_q \emptyset_{mg} - \frac{B_v}{p} w_e - T_L\right) \qquad (6)$$

However, the q -axis current i_q is the output of the inner-loop control system and is therefore not available for the manipulation in the outer loop. Instead, the control used is the set-point signal for the q -axis current i^*_q, and from the inner closed-loop system, the relationship between the output i_q and the set point i^*_q can be approximated by,

$$\dot{i}_q = -\frac{1}{\propto} i_q + \frac{1}{\propto} i^*_q \qquad (7)$$

Where α is the time constant of a first-order approximation and its value can be determined from the dominant pole of the inner closed-loop System. The continuous-time state-space model for the outer-loop control system is formed and is then discretized with a sampling period T_s. The key reason for using the continuous-time model to approximate the inner closed-loop system is because there is a difference between the sampling rates of inner and outer loops. Typically, the sampling rate for the inner loop is about twice as fast as that for the outer loop.

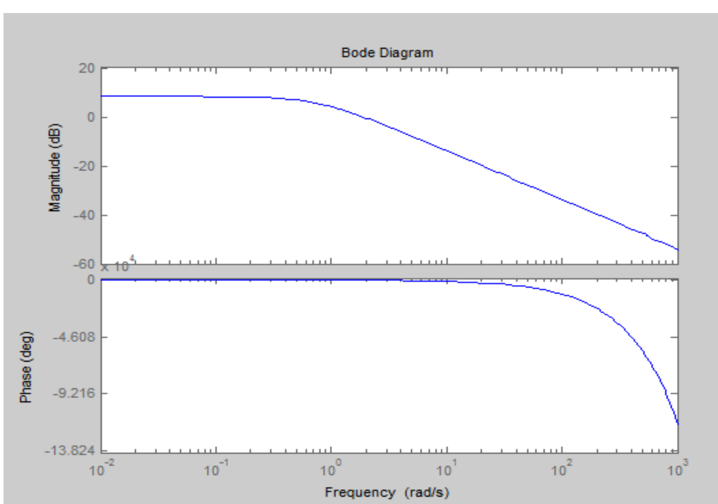

Figure 2 Simulation for Stability Test Of PMSM

4. SIMULATION RESULTS

Simulation for stability test of PMSM

The bode plot is formed to check the stability of the PMSM, but the bode plot shown that the motor is running in unstable condition. So we need to make the motor to run in stable condition. For that the inner loop current gain and the outer loop speed control are made.

Simulation of current of PMSM by inner loop control

The current control is made separately as the inner loop and the simulated output is shown below in the fig .3

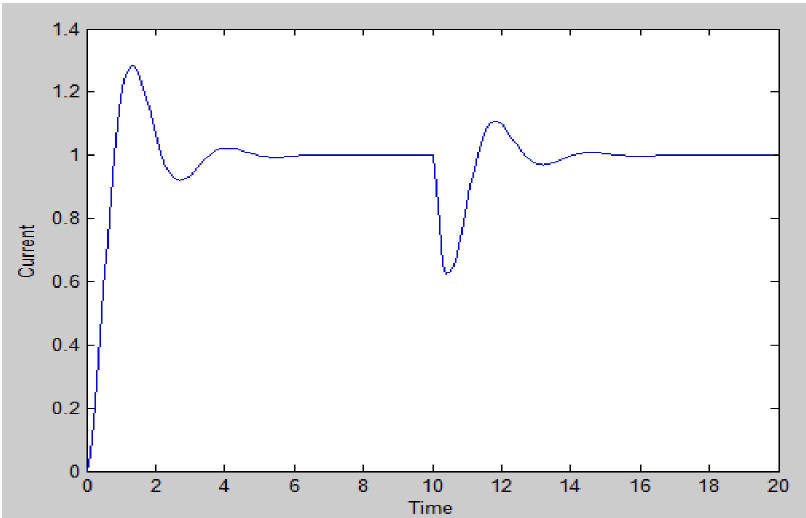

Figure 3 Simulation of Current of PMSM by Inner Loop Control

Error current after inner loop control

The values three different error values are found to check the performance of the PMSM and the error values are found to be more and we can come to a conclusion that the controlling of the current alone cannot make the performance of the special electric motor better. So we go for the speed control of the motor separately as the outer loop speed control.

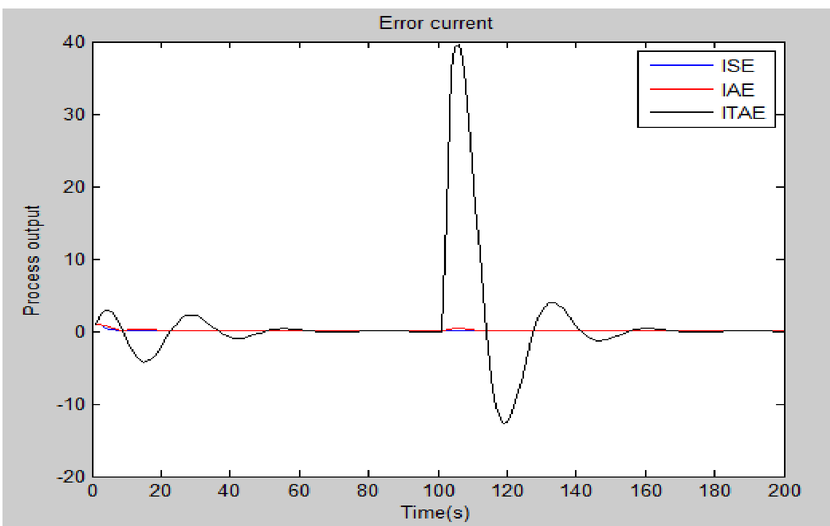

Figure 4 Error Current after Inner Loop Control

Simulation of speed of PMSM by outer loop control

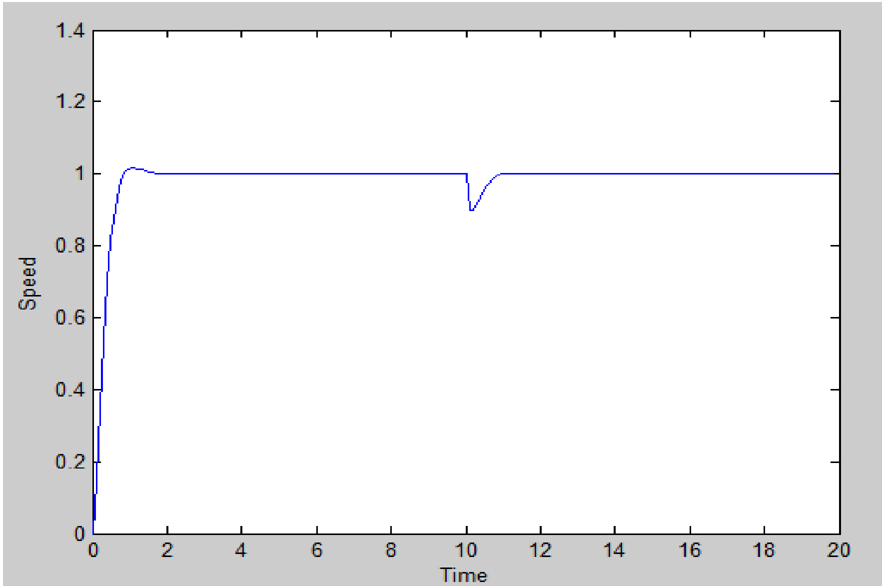

Figure 5 Simulation of Speed of PMSM by Outer Loop Control

Here in this simulation the setting time is reduced and the performance is also improved when compared to that of the current control.

Error speed after outer loop control

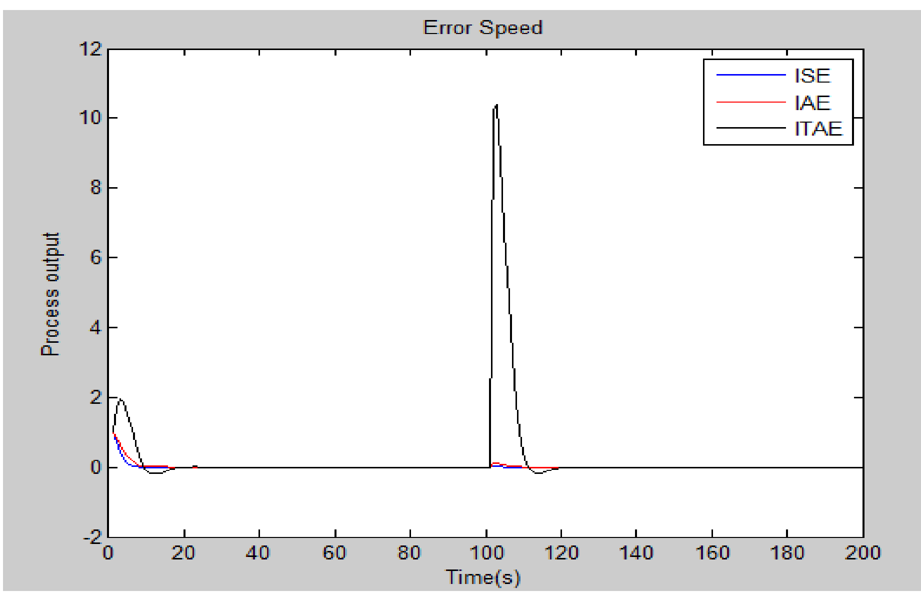

Figure 6 Error Speed after Outer Loop Control

Comparison of using single MPC and cascaded MPC

The comparisons of performance of the PMSM using the single MPC and the cascaded MPC are given below and the one with cascaded MPC is found to be better in performance than one with the single MPC.

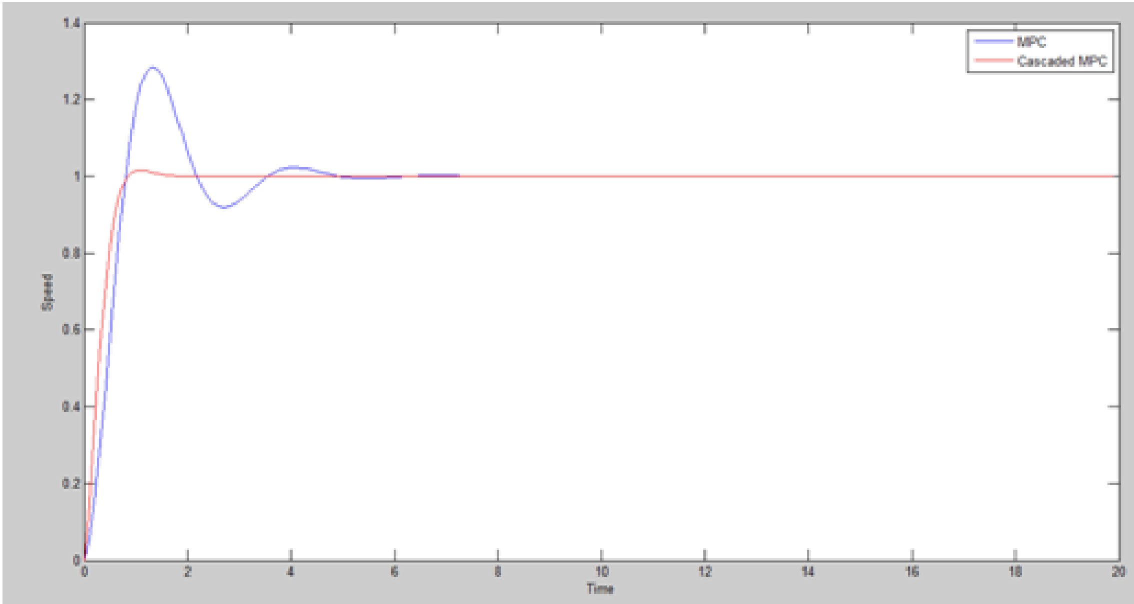

Figure 7 Comparisons of Using Single MPC and Cascaded MPC

5. CONCLUSION

This paper has developed a cascade MPC structure for high performance speed control of a PMSM with speed ripple minimization. The inner-loop MPC provides fast feedback control action to reduce the effects of disturbance, nonlinearities, and model parameter uncertainty. The outer-loop MPC is embedded with the zero frequency mode for start-up and an extra frequency mode for minimizing the speed ripples in steady state operation. The MPC design is based on the per-unit model of the PMSM, and experimental results confirm the potential of this control scheme. It is also evident from the experimental results that smooth transition of the control signal has been achieved when the controller structure changes in real time.

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